Characteristics of boundary layer structure during a persistent haze event in central Liaoning City Cluster, Northeast China

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Keywords:	Haze event, Thermal inversion layer, Atmospheric boundary layer, Northeast China
Speciality:	Atmospheric physics, Atmospheric boundary layer, Atmospheric environment

Dear Dr. Hu,

Thank you very much for your work and the reviewers' comments. We revised the original manuscript in accordance with all the comments and proof-read the manuscript to minimize typographical, grammatical and bibliographical errors. The responses to the comments has been listed as following:

Reviewer: 1

In this study, the characteristics of ABL during a haze event from 16-21 December 2016 in the central Liaoning were investigated using the air quality measurements, sounding data, LiDAR observations and reanalysis. Negative correlation between PM and BLH were found. And the southerly winds of ABL could brought water vapor and pollutants from the southern regions and play a role in exacerbating the air pollution. Besides, the evolution of wind vector and temperature of ABL were analyzed. This study will advances the understanding of the associations between the ABL structures/processes and aerosol pollutions in Liaoning, thus, I recommend its publication, subject to minor revisions.

1. During the studied period, since the aerosol concentration was quite high (Table 1), it is unnecessary to distinguish the "haze" and "fog" during this studied period. It is better to use the "haze" rather than the "haze-fog" to name this event.

Response: According to your suggestion, the event is classified as a haze event in the revision, as shown in Section 3.1.1.

2. The evolution of synoptic patterns (e.g., Liu et al., 2013, Hu et al., 2014, Miao et al.,

2017) during this pollution episode should be given, which strongly impacted ABL structures, the prevailing winds, and aerosol transport pathways. The synoptic patterns can be shown by using the ERA-Interim reanalysis.

Response: The surface weather maps from KMA (Korea meteorological Administrator) during the haze event have been added into the revision, as shown in Fig. 3. The relative analysis on the synoptic conditions during the haze event was given in Section 3.1.4.

3. How to calculate the BLH using the sounding data? More details should be given.

Response: In the revision, the method to calculate ABLH was rewritten. Line 186-190, "The atmospheric boundary layer height (ABLH) can be estimated by using the vertical potential temperature profiles from sounding data based on the theory of boundary layer evolution (Stull, 1988), with ABLH estimated at the altitude where the potential temperature first exceeds the minimum potential temperature within the boundary layer by 1.5 K (Nielsen-Gammon et al., 2008; Hu et al., 2014)".

4. In addition to the time series of aerosol concentrations shown in Fig. 2, the evolution of 2-m temperature, 2-m relative humidity, 10-m wind can be presented and analyzed to better understand this event.

Response: Fig. 2 has been modified according to your suggestion, including the hourly variations of PM concentrations, atmospheric visibility, air temperature, relative humidity, wind speed, and wind direction. The relative analysis on the surface meteorological conditions is added in Section 3.1.3.

5. The ending times of HYSPLIT for Shenyang, Anshan, Fushun, and Benxi should be presented in section 2.5.

Response: According to your suggestion, the ending time of back trajectory analyses is listed in Table 1 in Section 2.4.

Table 1 Information of back trajectory simulation

City	Position	Target altitude	Ending time
Shenyang	123.50°E, 41.77°N	200, 500, and 1000 m AGL	15:00 LT on December 16, 2016
Anshan	123.00°E, 41.08°N	200, 500, and 1000 m AGL	03:00 LT on December 17, 2016
Fushun	123.95°E, 41.88°N	200, 500, and 1000 m AGL	06:00 LT on December 17, 2016
Benxi	123.78°E, 41.32°N	200, 500, and 1000 m AGL	12:00 LT on December 17, 2016

6. Can the authors provide the LiDAR backscatter signal to better understand the evolution of BLH and aerosol pollution?

Response: The LiDAR backscatter data during this haze event have been used in another paper that has been submitted to JMR. Therefore, we did not show the data in this paper. In addition, considering that there is a large uncertainty in the ABLH determined by LiDAR, we only used the balloon sounding data in this work.

7. Some important previous studies about the ABL and aerosol pollution are suggested to be properly summarized in the Introduction (e.g., Hu et al., 2016; Ye et al., 2015; Miao et al., 2015; Miao et al., 2017).

Response: Thank you for the suggestion. These references have been cited in the revision.

References:

Liu, X.G., Li, J., Qu, Y., Han, T., Hou, L., Gu, J., Chen, C., Yang, Y., Liu, X., Yang, T., Zhang, Y., Tian, H., Hu, M., 2013. Formation and evolution mechanism of regional haze: A case study in the megacity Beijing, China. Atmos. Chem. Phys. 13, 4501–4514. doi:10.5194/acp-13-4501-2013

Hu, X.-M., Ma, Z., Lin, W., Zhang, H., Hu, J., Wang, Y., Xu, X., Fuentes, J.D., Xue, M., 2014. Impact of the Loess Plateau on the atmospheric boundary layer structure and air quality in the North China Plain: A case study. Sci. Total Environ. 499, 228–237. doi:10.1016/j.scitotenv.2014.08.053

Hu, X.M., Li, X., Xue, M., Wu, D., Fuentes, J.D., 2016. The Formation of Barrier Winds East of the Loess Plateau and Their Effects on Dispersion Conditions in the North China Plains. Boundary-Layer Meteorol. 1–19. doi:10.1007/s10546-016-0159-4

Miao, Y., Hu, X.-M., Liu, S., Qian, T., Xue, M., Zheng, Y., Wang, S., 2015. Seasonal variation of local atmospheric circulations and boundary layer structure in the Beijing-Tianjin-Hebei region and implications for air quality. J. Adv. Model. Earth Syst. 7, 1–25. doi:10.1002/2015MS000522

Miao, Y., Guo, J., Liu, S., Liu, H., Li, Z., Zhang, W., Zhai, P., 2017. Classification of summertime synoptic patterns in Beijing and their associations with boundary layer structure affecting aerosol pollution. Atmos. Chem. Phys. 17, 3097–3110. doi:10.5194/acp-17-3097-2017

Ye, X., Song, Y., Cai, X., Zhang, H., 2016. Study on the synoptic flow patterns and boundary layer process of the severe haze events over the North China Plain in January 2013. Atmos. Environ. 124, 129–145.

doi:10.1016/j.atmosenv.2015.06.011

Specific comments:

1. Line 279, what is the "strengthening downdraft"?

Response: It has been deleted in the revision.

2. Line 292, what is the "dynamic stability"?

Response: The sentence has been deleted in the revision.

3. Line 328, should be ABLH.

Response: It has been corrected in the revision.

4. Line 359-362. "The air masses at the middle altitude … first occurred in Shenyang." This statements are not right. In my opinion, the transport pathways cannot explain why the haze event first occurred in Shenyang. Please remove. Instead, the transport pathways may demonstrate that in addition to the high local emissions of aerosols, the trans-boundary transport of aerosols from the NCP could play a role in exacerbating the air pollution.

Response: Thank you for your explanation. The statement has been deleted in the revision.

Reviewer: 2

General comments:

The manuscript intends to identify the characteristics of the atmospheric boundary layer structures and their evaluation that are associated with a persistent fog-haze event occurrence in Northeast China. The smoggy atmospheric boundary layer is an interesting topic for both meteorology and air quality studies, and deserves further studies. However, the manuscript is more like a report with general description rather than a research paper, especially the scientific questions of the study are not clear and the study did not provide enough interesting or new results. A deep scientific analysis is lacking. English writing needs significant improvement. I recommend major revisions to address the following comments.

Specific comments:

1. It is not clear to me what are the scientific questions or objectives of this study. The manuscript provides general descriptions of spatial and temporal variations in several important parameters during the event rather than deep analyses of the reasons causing such changes. The finding and conclusions obtained from the study are not new. Most of them are known even without this study.

Response: This manuscript presents the characteristics of boundary layer structure during a persistent regional haze-fog event over the central Liaoning City Cluster of Northeast China. Few studies discussed about the air pollution in Northeast China. It is an important topic in the field of atmospheric environment. The results are somewhat helpful to understand the effect of ABL structure on the formation and evolution of air pollution in this region.

2. The study investigated the event for the period from December 16 to December 22. However, the time series shows that the event started from late night of Dec. 18 or early morning on Dec. 19th in Shenyang, and then continued on the following two to three days (Figure 2). It is the same for other three cities. The authors should focus on the period of December 19-21 rather than the whole period of December 16-21.

Response: Thank you for the suggestion. In order to clearly exhibit the whole campaign, we showed the temporal variation of PM concentration and some surface meteorological parameters from December 16 to 21, 2016 (Fig. 2). However, we analyzed the characteristics of ABL structure only during December 18-21 in the revision, as shown in Fig. 5-8.

3. While the authors pointed out the importance of meteorological conditions to the air pollutant concentrations in different cities or regions, anthropogenic emissions could be another important factor causing the regional differences of air pollutants. However, the authors didn't include the impact of anthropogenic emissions on $PM_{2.5}$ and PM_{10} during their discussion.

Response: In the revision, we also mentioned the importance of emission to the haze formation. Line 363-366, "The transport pathways may demonstrate that in addition to the high local emissions of aerosols, the trans-boundary transport of aerosols from the North China Plain (NCP) could play a role in exacerbating the air pollution". Line 399-402, "In conclusion, the unfavorable meteorological conditions within ABL played as the external reason of this haze formation, besides the anthropogenic emissions of pollutants as the basic cause".

4. This is a typical case with alternative occurrence of fog and haze. It will be interesting if the authors add some comparisons of the characteristics of the atmospheric boundary layer between fog and haze occurrence days.

Response: During the studied period, since the aerosol concentration was quite high, we think it is better to use the "haze" rather than the "haze-fog" to name this event.

5. When the authors present spatial variations in winds and temperature (e.g., see Sections 3.2.1-3.2.3), it would be helpful to link $PM_{2.5}$ and PM_{10} with the changes of meteorological variables in the atmospheric boundary layer. I cannot see this linkage in the current submission.

Response: Such linkage between PM concentrations and meteorological parameters has been added in the revision. 1) linkage between PM and wind vector distribution, Line 287-294, "It can be seen that during 02:00–11:00 LT on December 18 wind speed at all heights below 2 km decreased rapidly with time, and wind direction rotated with increasing height in a clockwise direction. Meanwhile, PM concentrations at surface began to increase sharply (Fig. 2a). Weak southerly and southwesterly flows then prevailed until 11:00 LT on 19 December, corresponding with $PM_{2.5}$ increasing to approximately 300 μg m^{-3} (Fig. 2a). After, wind speed was still very small at low altitudes (< 600 m), whereas at high altitudes, winds fluctuated frequently, contributing to the fluctuation of PM concentrations". 2) linkage between PM and air temperature distribution, Line 301-303, "With the increasing PM concentrations during the haze event, T_a in the boundary layer decreased obviously, and the depth of the warm advection declined until 14:00 LT on December 20". 3) linkage between PM and potential temperature profiles, Line 309-324," To clearly outline the atmospheric stability in ABL, Fig. 7 shows potential temperature profiles in Shenyang at 05:00, 11:00, 17:00 and 23:00 LT from December 18 to 22, 2016. From 05:00 LT on December 18 to 05:00 LT on December 19, a potential temperature inversion layer existed from the surface to the height of 1500 m, and the inversion intensity gradually increased with time. During this period, the surface $PM_{2.5}$ concentration increased from 123 to 209 μg m^{-3}. After, θ varied very small at the low altitudes of ABL (< 800 m), but the enhancement of the potential temperature inversion was apparent at high altitudes of ABL. The potential temperature inversion intensity gradually increased from 8.9 K km^{-1} at 17:00 LT on December 19 to 15.8 K km^{-1} at 23:00 on December 20. Additionally, the bottom of inversion height gradually decreased from approximately 900 m at 17:00 LT on December 19 to approximately 300 m on 23:00 LT on December 20, corresponding to a very high PM concentrations on the following day. After that, the bottom of inversion height increased to 900 m again at 11:00 LT on December 22, which strengthened the vertical mixing of air pollutants and favored with the dilution of air pollutants at surface." 4) linkage between PM and ABLH, Line 337-344, "From 02:00 LT on December 18 to 11:00 LT on December 19, ABLH was mostly below 400 m, and $PM_{2.5}$ and PM_{10} concentrations during this period reached 265 and 370 μg m^{-3}. When the ABLH increased rapidly to 900 m at 14:00 LT on December 19 and remained larger than about 600 m until 08:00 LT on December 20, $PM_{2.5}$ and PM_{10} concentrations dropped to 142 and 180 μg m^{-3}, respectively. As ABLH remained lower than 400 m from midday on December 20 to midday December 21, the air pollution in the near-surface layer enhanced again."

6. Lines 39-41: The ECMWF results (i.e., the prevailing southerly winds) are inconsistent with the back trajectory model (HYSPLIT) results (see Fig.8).

Response: The ECMWF results are calculated based on the daily mean data at 10 m height, while the HYSPLIT results were simulated at 200, 500, and 1000 m. The difference between the two results is probably due to the difference of target height and time resolution.

7. Figure 1: two panels can be combined.

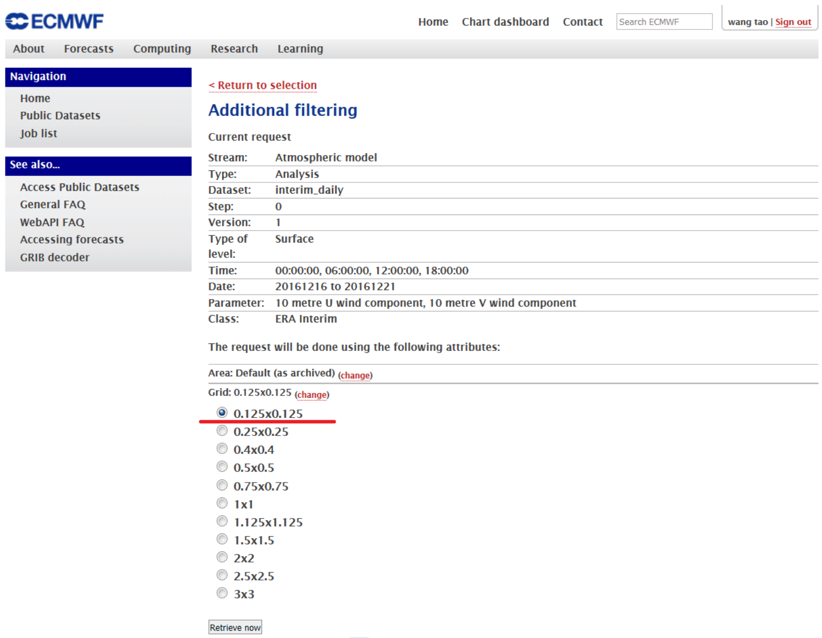
Response: Thank you for the suggestion. However, the scale of Fig. 1b is much smaller than that of Fig. 1a. Considering the clearness of Fig. 1b, we think it's better to keep the two panels.

8. Several terminology abbreviations are not standard. They include Wind speed (U) and local time (LT).

Response: These abbreviations have been corrected in the revision.

9. L160-161: are you sure that the resolutions of ECMWF are 0.125° × 0.125°?

Response: The resolutions of ECMWF are definitely 0.125° × 0.125°, as shown in the following picture.



10. Lines 187-189: I don't think the ABLH is defined correctly.

Response: In the revision, the method to calculate ABLH was rewritten. Line 186-190, "The atmospheric boundary layer height (ABLH) can be estimated by using the vertical potential temperature profiles from sounding data based on the theory of boundary layer evolution (Stull, 1988), with ABLH estimated at the altitude where the potential temperature first exceeds the minimum potential temperature within the boundary layer by 1.5 K (Nielsen-Gammon et al., 2008; Hu et al., 2014)".

11. L201, HYSPLT has been defined already.

Response: The full name of HYSPLT in this sentence was deleted in the revision.

12. L233-235: The sentence needs to be rewritten. In fact, there are many sentences like this. Please do careful check throughout the manuscript.

Response: The definition of haze event has been modified in the revision, Line 201-206, "A haze event is characterized by an apparent decrease of *VIS* less than 10 km and ambient *RH* smaller than 80% lasting for several hours (Fu et al., 2008; Leng et al., 2016). Under the conditions of 80% < *RH* < 90%, the event is usually regarded as a complex of haze-fog co-occurring or transition (Leng et al., 2014; 2016), while under the conditions of *RH* ≥ 90%, it is referred to as a fog event".

13. L246-250: SY, AS, FS, BX are not defined in Table 1. In addition, I do not think that Table 1 is necessary since it does not provide enough useful information for the discussion.

Response: Thank you for your suggestion. The original table has been deleted in the revision. Table 1 Statistical summary (mean ± standard deviation) of particulate matter (PM) concentrations and selected surface meteorological parameters during haze and fog periods in the four cities. The letter "H" and "F" represents haze and fog, respectively.

14. Figure 3: What data are used for the plotting? This information should be included in the figure caption. Labels of both X- and Y-axis and text size inside the figure are too small.

Response: The plotting is obtained from the ECMWF reanalysis data. The figure caption have been modified as "Fig. 4. Spatial variations of the daily mean wind field retrieved from the ECMWF reanalysis data over Liaoning province from December 16 to 21, 2016. SY, FS, AS, and BX represent Shenyang, Fushun, Anshan, and Benxi, respectively". In addition, larger size was set for the labels of both X- and Y-axis and text inside Fig. 4.

15. Lines 273-293: The authors divided the event into five periods. How this period definition can be linked with the periods defined in Table 1? For instance, seven periods were defined for the event observed in Shenyang. It is very confused to readers.

Response: The five periods for evolution of winds vertical distribution have been canceled in the revision, to avoid the unnecessary confusion as you mentioned.

16. Again, for the Section 3.2.4, the authors should focus on how the changes of PBLH or ABLH affect the surface PM concentrations rather than the comparison between two different measurements.

Response: First of all, considering that there is a large uncertainty in the ABLH determined by LiDAR, we only used the balloon sounding data to obtain ABLH. Secondly, the effect of ABLH on PM concentrations have been discussed further in Section 3.2.4. Line 333-347, "Decreasing the height of ABL can normally hold the pollutants within the shallow surface layer, suppress the vertical atmospheric dilution and finally lead to regional environment shrouded by pollution (Kim et al., 2007; Leng et al., 2016). The ABLH estimated using sounding data was plotted in Fig. 8. The regular diurnal variation of ABLH, i.e., highest in the middle of the day and lowest at nighttime, was not so typical during heavy pollution period. From 02:00 LT on December 18 to 11:00 LT on December 19, ABLH was mostly below 400 m, and $PM_{2.5}$ and PM_{10} concentrations during this period reached 265 and 370 μg m^{-3}. When the ABLH increased rapidly to 900 m at 14:00 LT on December 19 and remained larger than about 600 m until 08:00 LT on December 20, $PM_{2.5}$ and PM_{10} concentrations dropped to 142 and 180 μg m^{-3}, respectively. As ABLH remained lower than 400 m from midday on December 20 to midday December 21, the air pollution in the near-surface layer enhanced again. On the whole, the ABLH measured by ball sounding was typically below 400 m during heavy pollution episodes. Such shallow ABL led to high PM concentration in the near-surface layer".

17. What is the ending time of these back trajectory analyses which are presented in Section 3.3 and Figure 8?

Response: The ending time of back trajectory analyses is listed in Table 1 in Section 2.4.

Table 1 Information of back trajectory simulation

City	Position	Target altitude	Ending time
Shenyang	123.50°E, 41.77°N	200, 500, and 1000 m AGL	15:00 LT on December 16, 2016
Anshan	123.00°E, 41.08°N	200, 500, and 1000 m AGL	03:00 LT on December 17, 2016
Fushun	123.95°E, 41.88°N	200, 500, and 1000 m AGL	06:00 LT on December 17, 2016
Benxi	123.78°E, 41.32°N	200, 500, and 1000 m AGL	12:00 LT on December 17, 2016

18. Abstract and conclusions need to be rewritten with more precise language or sentences.

Response: Thank you for the suggestion. The abstract and conclusions parts have been carefully modified in the revision.

19. The manuscript is not well written. I am going to list all the sentence structure issues and grammar errors here since there are quite lot in the paper. The manuscript needs significant improvement.

Response: We revised the original manuscript in accordance with all the comments and proof-read the manuscript to minimize typographical, grammatical and bibliographical errors. The English has been professionally checked by Textcheck Inc..

Reviewer: 3

This manuscript presents the characteristics of boundary layer structure during a persistent regional haze-fog event over the central Liaoning City Cluster of Northeast China. Few studies discussed about the air pollution in Northeast China. It is an important topic in the field of atmospheric environment. Generally, the manuscript is well organized and prepared. It is within the scope of the journal. It merits to be published after some revisions.

1. P11 Line 218, “with a mean visibility of 1.94 km (Fig.2a)”, but visibility wasn’t illustrated in Fig.2a.

Response: The temporal variation of atmospheric visibility and some meteorological parameters were added into Fig. 2.

2. Fig.2a, Why the Author highlight the first peak at 00:00 19 Dec. There is also a peak before that, approximately 20:00 18 Dec. Why not use it as the first peak?

Response: In order to avoid the confusion as you mentioned, we deleted the arrows that represent the first PM peak in Fig.2.

3. P12 line 233-235, It is important to distinguish haze and fog, In Table 1, why the $PM_{2.5}$ concentration in fog episode is even higher than that in Haze episode? I have highlighted some of that as following.

Response: During the studied period, since the aerosol concentration was quite high, we think it is better to use the “haze” rather than the “haze-fog” to name this event.

4. P11 line 224-227 “It is interesting to find that the first PM peak occurred in Shenyang at first, followed by Anshan, Fushun, and then Benxi, which was likely related to the regional transport of air pollutants.” The paper illustrated that there was a transport of pollutants from Shenyang, Anshan, Fushun and Benxi (Fig.2), but In Fig. 8, the back trajectory results weren’t in accordance with the above pathway. E.g. In the 200 m back trajectory (the green line in 2 Fig.8), the air mass for Anshan, Fushun and Benxi wasn’t from Shenyang. Could the author give more explanation of that?

Response: The statement in the original manuscript is not rigorous, therefore, we deleted this statement in the revision. Actually, the transport pathways may demonstrate that in addition to the high local emissions of aerosols, the trans-boundary transport of aerosols from the North China Plain could play a role in exacerbating the air pollution.

Editor(s)' Comments to Author:

Editor: 1

Comments to the Author:

In addition to the reviewers' comments, the editor has the following concerns:

1. The boundary layer structure during the haze event is not clearly illustrated currently.

Response: The boundary layer structure and its effect on PM concentrations were further discussed in Section 3.2 in the revision.

2. Temperature profiles shown in Fig. 6 is not adequate to illustrate boundary layer structure, using potential temperature profiles instead is recommended.

Response: The potential temperature profiles are used to illustrate boundary layer structure in the revision. The plotting is shown in Fig. 7.

3. Lidar data is interesting and very useful to investigate haze events. But currently it is not nicely utilized. It is well known that there are large uncertainties during PBLH retrieval process based on Lidar data. Thus derivation of Fig. 7 needs more discussion. Also time-height diagram of Lidar backscattering is needed.

Response: Thank you for the reminding. The LiDAR backscatter data during this haze event have been fully used in another paper that has been submitted to JMR. Additionally, considering the large uncertainty in estimation of ABLH using LiDAR data, the LiDAR data were not used in the revision.

4. Time series of other meteorological variables are needed along with Fig. 2.

Response: In the revision, some meteorological parameters were added in Fig.2, including atmospheric visibility, wind speed, wind direction, relative humidity and air temperature in the four cities from December 16 to 21, 2016.

5. Figure captions need to be self-explanatory. Please improve figure captions, e.g., is the data from reanalysis or station observations?

Response: Figure captions have been modified in the revision.

Fig. 2. Temporal variations of hourly mean (a–d) $PM_{2.5}$ and PM_{10} mass concentrations from environmental monitoring stations and atmospheric visibility, (e–h) wind speed

and wind direction, and (i–l) relative humidity and air temperature at 2 m height from meteorological stations in Shenyang, Anshan, Fushun and Benxi from December 16 to 21, 2016. The dash lines in (a–d) are visible at 10 km.

Fig. 4. Spatial variations of the daily mean wind field retrieved from the ECMWF reanalysis data over Liaoning province from December 16 to 21, 2016. SY, FS, AS, and BX represent Shenyang, Fushun, Anshan, and Benxi, respectively.

Fig. 5. Vertical distribution of vector wind from the sounding data in Shenyang from 02:00 LT on December 18 to 02:00 LT on December 22, 2016.

Fig. 6. Vertical distribution of air temperature from the sounding data in Shenyang 02:00 LT on December 18 to 02:00 LT on December 22, 2016.

Fig. 7. Potential temperature profiles from the sounding data in Shenyang at 02:00, 08:00, 14:00 and 20:00 LT from December 18 to 22, 2016.

Fig. 8. Evolution of atmospheric boundary layer height (ABLH) from the sounding data in Shenyang.

6. What is "stable wind direction"? Please improve English writing.

Response: It has been deleted in the revision, and we improve the English writing carefully.

Li Xiaolan and other co-authors

August 23, 2017

Characteristics of boundary layer structure during a persistent haze event in central Liaoning City Cluster, Northeast China

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ABSTRACT

The characteristics of boundary layer structure during a persistent regional haze event over the central Liaoning City Cluster of Northeast China from December 16 to 21, 2016 were investigated based on measurements of particulate matter (PM) concentrations and boundary layer data. During the observational period, the maximum hourly mean $PM_{2.5}$ and PM_{10} concentrations in Shenyang, Anshan, Fushun and Benxi ranged from 276 to 355 μg m^{-3} and from 378 to 442 μg m^{-3}, respectively, and the lowest hourly mean atmospheric visibility (*VIS*) in different cities ranged from 0.14 to 0.64 km. The central Liaoning City Cluster was located in the front of a slowly migrating high pressure and was mainly controlled by southerly winds that brought water vapor from the Bohai Sea and contributed to a high ambient relative humidity (*RH*) condition (60–98%). Wind speed (*U*) within the atmospheric boundary layer (ABL) (< 2 km) decreased significantly and *U* at 2 m height mostly remained below 2 m s^{-1} during the hazy episodes, which was favorable for the accumulation of air pollutants. A potential temperature inversion layer existed throughout the entire ABL during the earlier hazy episode (from 05:00 LT on December 18 to 11:00 LT on December 19), and then a potential temperature inversion layer developed with the bottom gradually decreased from 900 m to 300 m. Such stable atmospheric stratification further weakened pollutant dispersion. Atmospheric boundary layer height (ABLH) estimated based on potential temperature profiles was mostly below 400 m and varied oppositely with $PM_{2.5}$ in Shenyang. In summary, weak winds due to calm synoptic conditions, strong thermal inversion layer, and shallow atmospheric boundary layer contributed to the formation and development of this haze event. The backward trajectory analysis revealed the sources of air masses and explained the different characteristics of the haze episodes in the four cities.

Key words: Haze event, Thermal inversion layer, Atmospheric boundary layer, Northeast China

1. Introduction

Fog and haze are meteorological phenomena that may lead to severe near-surface weather (Zhang et al., 2014). Haze pollution in China has increased over the past three decades, particularly in city clusters, as a result of the rapidly developing economy, expansion of anthropogenic activities and urbanization (Shao et al., 2006; Fu et al., 2014; Wang et al., 2014a). In recent years, heavy and persistent haze events have been observed in different regions of China (Ji et al., 2012; Liu et al., 2015; Peng et al., 2016), resulting in atmospheric visibility reduction, increased air pollution, and risks to public health (Chan and Yao, 2008; Che et al., 2014; Chen et al., 2012; Shen et al., 2015; Zhang et al., 2014; Tang et al., 2017).

Haze formation is closely related to meteorological conditions and high aerosol mass loadings (Wang et al., 2014b). In the northern part of China, heavy air pollution is easy to occur in the heating season or during periods when agricultural residues are burned mainly due to large pollutant emissions and unfavorable meteorological conditions for pollutant dispersion (Fu et al., 2014; Wang et al., 2014b; Zheng et al., 2015; Chen et al., 2016). Since the heating season begins earlier and lasts longer in Northeast China and is combined with burning of agricultural residues, haze occurs frequently during winter in this region. For example, a heavy and persistent haze event with a maximum $PM_{2.5}$ concentration exceeding 1000 μg m^{-3} occurred during November 1–8, 2015 in Shenyang and profoundly shocked both the public and the government (http://news.sina.com.cn/c/nd/2015-11-08/doc-ifxknutf1607479.shtml). Several studies have reported that haze pollution in Northeast China is serious (Cui et al., 2015), with an increasing trend in particulate matter (PM) observed at some stations in this region from 2006 to 2014 (Wang et al., 2015c).

Many efforts have been made to identify the meteorological causes of haze events involving the effects of surface meteorological conditions, synoptic systems, climatic background, and local atmospheric circulation induced by the topography (Chen et al., 2008; Liu et al., 2009; Zhu et al., 2012; Hu et al., 2014; 2016). Chen et al. (2008) indicated that pollution formation is related to high-pressure conditions and successive low-pressure systems over North China. Zhu et al. (2012) demonstrated that the weakened monsoon circulation of recent decades has made a significant contribution to trapping pollutants over Eastern China. The modeling results reported by Miao et al. (2015, 2017) revealed that local atmospheric circulation plays an important role in surface air pollution over the Beijing–Tianjin–Hebei region. In addition, the structure of the atmospheric boundary layer (ABL) is also crucial to the formation and evolution of haze (Wang et al., 2006; Yang et al., 2010; Lu et al., 2011; Tang et al., 2016, Ye et al., 2016). Wu et al. (2009) and Sun et al. (2013) found that the vertical dynamic and thermal variations within the ABL influence pollutant concentrations. Quan et al. (2013) compared ABL evolution during clear and hazy conditions in Tianjin and considered the possibility of a positive feedback cycle between atmospheric aerosols and lower ABL height, which would induce heavy surface-level pollution in cities. Liu et al. (2015) analyzed ABL characteristics during a typical haze process in January 2014 over the Pearl River Delta region and found that weak wind, low ABL height, and a thermal inversion layer under stable atmospheric conditions were major reasons for haze formation. Hu et al. (2014) investigated the impact of the Loess Plateau on the ABL structure and air quality in the North China Plain (NCP). Based on field measurements similar studies have also been conducted in other megacities or regions, such as the Beijing–Tianjin–Hebei region (Wang et al., 2014a; Liao et al., 2014), Xi'an in Western China (Wang et al., 2016), and Eastern China (Li et al., 2015; Peng et al., 2016), but such studies are still very rare in Northeast China (Zhang et al., 2010a, 2010b; Liu et al., 2011). These previous studies have contributed to our understanding of the effects of ABL evolution on the changes in surface air pollution and provide a reference for studies of the interaction of ABL meteorology and aerosols in haze modeling and prediction (Wang et al., 2015a, 2015b).

In this study, the characteristics of ABL structure during a persistent, severe regional haze event over the central Liaoning City Cluster during December 16–21, 2016 were analyzed, using the vertical profiles of ABL meteorological parameters and surface PM concentrations and combined with horizontal wind fields retrieved from the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis data and back trajectory analyses from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. In Section 2, a brief introduction to the study area and details of the data and methods are described. The results and discussion, given in Section 3, mainly address temporal variation in PM concentrations and surface meteorological parameters, and the horizontal and vertical structure of the boundary layer. Finally, the conclusions of the study are presented in Section 4.

2. Data and methods

2.1 Description of the study area

Liaoning province is an industrial region that has made a substantial contribution to the economic development of Northeast China (Che et al., 2015). Our study focused on the central Liaoning City Cluster, which comprises Shenyang, Anshan, Fushun, and Benxi (Fig. 1a). These four urban cities are located in a heavily populated industrial region of Northeast China (118.53–125.46°E, 38.43–43.26°N), a major source area for aerosol pollution originating from a variety of human activity, industrial, and transportation sources (Ma et al., 2012; Zhao et al., 2013a; Che et al., 2015). Particularly in winter, emissions from coal burning for domestic heating are a well-established source of pollution (Zhao et al., 2013b; Che et al., 2015).

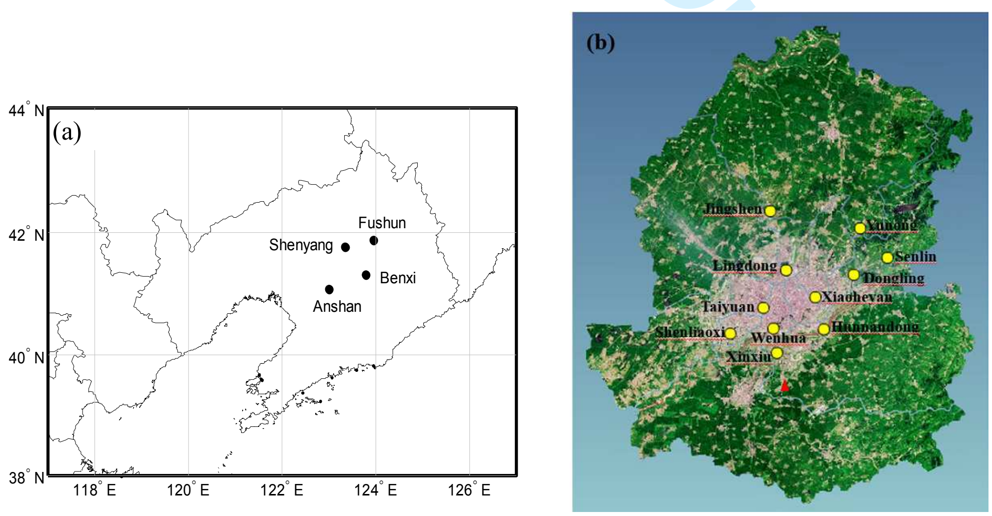


Fig. 1. (a) Geographical locations of four cities in the central Liaoning City Cluster

of Northeast China, and (b) positions of eleven environmental monitoring stations (yellow circle) and the boundary layer experiment (red triangle) in Shenyang.

2.2 PM concentrations and surface meteorological parameters

Large-scale regional haze pollution in recent years has been characterized by high concentrations of $PM_{2.5}$ (Wang et al., 2014a). In this study, the hourly mass concentrations of PM_{10} and $PM_{2.5}$ in Shenyang, Anshan, Fushun, and Benxi during a typical haze event from December 16 to 21, 2016 were obtained from the Liaoning real-time air quality monitoring system (http://211.137.19.74:8089/). There are eleven monitoring stations located in Shenyang, seven in Anshan, and six each in Fushun and Benxi. The ambient real-time particulate monitor is used to measure the concentrations of $PM_{2.5}$ (Model 5030i, Thermo. Sci.) and PM_{10} (Model 5014i, Thermo. Sci.) at each station. The $PM_{2.5}$ and PM_{10} data used in this study were the averages of all the stations in each city and were considered to be representative of the entire city.

The simultaneous hourly mean surface meteorological parameters, i.e., wind speed (U), wind direction (WD), air temperature (T_a), relative humidity (RH), and atmospheric visibility (VIS), from the national weather stations in the four cities were used to analyze the surface meteorological conditions.

2.3 Boundary layer structure

The ECMWF reanalysis data, with a spatial resolution of 0.125° × 0.125°, were used to retrieve the horizontal flow fields at 10 m above ground level (AGL) over Liaoning from December 16 to 21, 2016. The ECMWF data were obtained four times a day, at 00:00, 06:00, 12:00, and 18:00 Coordinated Universal Time (UTC), and can be freely downloaded from http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/.

A boundary layer observational campaign was conducted from 11:00 Local Time (LT) on December 17 to 14:00 LT on December 23, 2016 in Baitapu Town (123.4160°E, 41.6841°N), about 8 km from the southern edge of the main urban zone of Shenyang (Fig. 1b). The Model CZTK-1 sounding system, developed by the Institute of Atmospheric Physics of the Chinese Academy of Sciences, was used to measure the vertical distributions of *U*, *WD*, T_a, and *RH*, with detective resolution of 0.1 m s^{-1}, 0.1°, 0.1□, and 0.1%, respectively. Sounding balloons were released at an open balcony of a low building (height < 3 m) eight times per day, at 02:00, 05:00, 08:00, 11:00, 14:00, 17:00, 20:00, and 23:00 LT, and a total of 50 groups of profile data were obtained. The ascending velocity of the sounding balloons was about 150 m min^{-1}, and sounding data were recorded at an interval of 1 s. The detection duration was about 20–40 min, and the detection height usually reached up to 1500–4500 m. It should be noted that no precipitation occurred from December 17 to 21 during the haze event but snow weather lasted during December 22–23 after the haze event. Following the methods used in Liu et al. (2015), vector winds at different observational heights were first calculated based on the vertical profiles of *U* and *WD*, and then interpolated at each 50-m AGL. The profiles of T_a and *RH* were averaged every 10 m after data quality control, and then potential temperature (θ) was calculated.

The atmospheric boundary layer height (ABLH) can be estimated by using the vertical potential temperature profiles from sounding data based on the theory of boundary layer evolution (Stull, 1988), with ABLH estimated at the altitude where the potential temperature first exceeds the minimum potential temperature within the boundary layer by 1.5 K (Nielsen-Gammon et al., 2008; Hu et al., 2014).

2.4 Back trajectory analyses

The HYSPLIT model from the National Oceanic and Atmospheric Administration (NOAA) was used to analyze the transport path of atmospheric pollutants during the haze event (Draxler and Polph, 2003). Two-day back trajectory analyses were conducted for the four cities and the information is listed in Table 1.

Table 1 Information of back trajectory simulation

City	Position	Target altitude	Ending time
Shenyang	123.50°E, 41.77°N	200, 500, and 1000 m AGL	15:00 LT on December 16, 2016
Anshan	123.00°E, 41.08°N	200, 500, and 1000 m AGL	03:00 LT on December 17, 2016
Fushun	123.95°E, 41.88°N	200, 500, and 1000 m AGL	06:00 LT on December 17, 2016
Benxi	123.78°E, 41.32°N	200, 500, and 1000 m AGL	12:00 LT on December 17, 2016

3. Results and discussion

3.1 Overview of the haze event in the central Liaoning City Cluster

3.1.1 Identification of hazy episode

A haze event is characterized by an apparent decrease of *VIS* less than 10 km and ambient *RH* smaller than 80% lasting for several hours (Fu et al., 2008; Leng et al., 2016). Under the conditions of 80% < *RH* < 90%, the event is usually regarded as a complex of haze-fog co-occurring or transition (Leng et al., 2014; 2016), while under the conditions of *RH* ⩾ 90%, it is referred to as a fog event.

Figure 2 depicts the temporal variations of hourly mean PM mass concentrations and some surface meteorological parameters in Shenyang, Anshan, Fushun and Benxi from December 16 to 21, 2016. As shown in Fig. 2a–d, *VIS* remained below 10 km during December 17–21 in all cities except for Anshan where *VIS* declined to below 10 km after the midday of December 18. *RH* mostly ranged from 60% to 90% in Shenyang and Fushun and from 40% to 90% in Anshan and Benxi (Fig. 2i–l). Since $PM_{2.5}$ concentration was quite high during the whole period, this event is classified as a haze event in the present study. During the observational period, air quality in most cities reached Level 5 (daily air quality index > 200) according to the ambient air quality standards in China, which means the central Liaoning City Cluster suffered from a persistent and severe haze pollution.

3.1.2 Particulate mass concentration and atmospheric visibility

Overall, PM_{10} and $PM_{2.5}$ concentrations varied similarly during the haze event in all cities. The maximum hourly $PM_{2.5}$ in different cities ranged from 276 to 355 μg m^{-3} and the maximum hourly PM_{10} in different cities ranged from 378 to 442 μg m^{-3}. The lowest hourly *VIS* reached 0.14, 0.64, 0.18 and 0.63 km in Shenyang, Anshan, Fushun and Benxi, respectively (Fig.2a–d). Taken Shenyang as an example, the $PM_{2.5}/PM_{10}$ ratio averaged during the haze event reached 75.3% (not shown), which is consistent with results from previous literatures that low visibility is influenced markedly by fine particles in Northeast China (Ma et al., 2011; Zhao et al., 2013a, 2013b). During the haze event, $PM_{2.5}$ concentration was larger in Anshan (158.3 ± 22.2 μg m^{-3}) and Shenyang (157.9 ± 31.0 μg m^{-3}) and relatively smaller in Fushun (121.3 ± 48.9 μg m^{-3}) and Benxi (135.6 ± 60.8 μg m^{-3}). Comparing the variations of $PM_{2.5}$ and *VIS* in Fushun with those in Anshan, it is interesting to find that Anshan had larger $PM_{2.5}$ concentration but still higher visibility during December 17–18, which was probably due to a lower *RH* (40–60%) condition in Anshan. Some previous studies have indicated that an increase in *RH* within a certain range can cause significant *VIS* degradation (Stock et al., 2011; Liu et al., 2012).

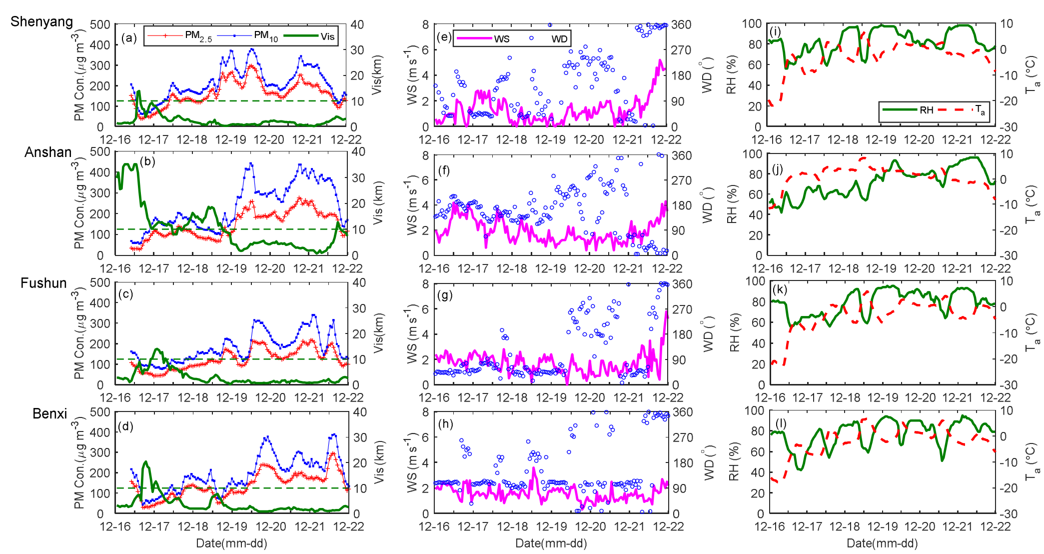


Fig. 2. Temporal variations of hourly mean (a–d) $PM_{2.5}$ and PM_{10} mass concentrations from environmental monitoring stations and atmospheric visibility, (e–h) wind speed and wind direction, and (i–l) relative humidity and air temperature at 2 m height from meteorological stations in Shenyang, Anshan, Fushun and Benxi

from December 16 to 21, 2016. The dash lines in (a–d) are visible at 10 km.

3.1.3 Surface meteorological conditions

Wind speed at 2 m height was lower than 2 m s^{-1} for most of the hazy period but increased to larger than 4 m s^{-1} on December 21 in all cities except for Benxi (Fig. 2e–h). Wind direction in Shenyang changed frequently but was basically southeast or southwest during the haze event (Fig. 2e). In other three cities, *WD* also turned into southeast or southwest when PM concentrations increased rapidly on December 19 (Fig. 2f–h). T_a mostly ranging from -10 to 5 ℃, and correlated negatively with ambient *RH* (Fig. 2i–l).

3.1.4 Synoptic situation

The surface weather maps at 00:00 UTC on December 18–21 are shown in Fig. 3. The central Liaoning City Cluster was located in the front of a weak and slowly migrating high pressure system on December 18–20 (Fig. 3a–c). The weak pressure gradients represented by very sparse isobaric lines resulted in weak large-scale air circulation and low wind speed in the near-surface layer in this region. Such stable synoptic conditions favored the accumulation of atmospheric pollutants and inhibited their horizontal dilution. With the cold high pressure near the Baikal Lake moving towards the southeast, the surface isobaric lines over this region became much denser on December 21 (Fig. 3d), and strong winds were conductive to the dispersion of air pollutants.

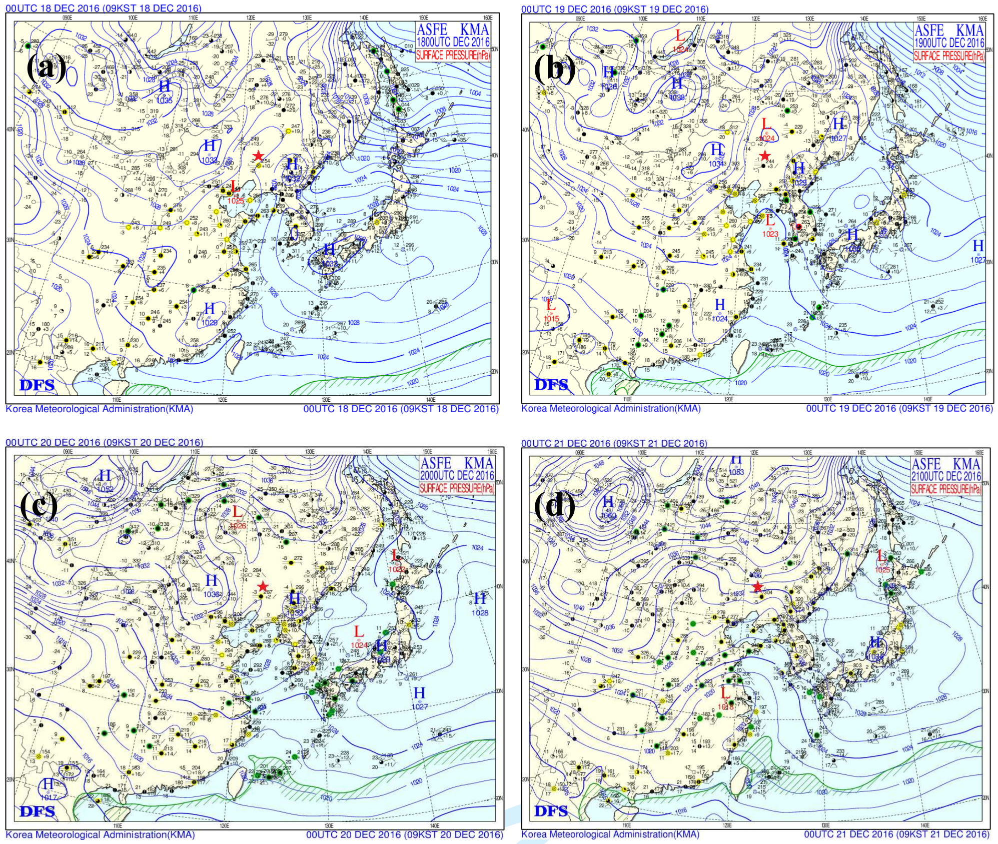


Fig. 3. Surface weather maps at 00:00 UTC from December 18 to 21, 2016. The red stars denote Shenyang.

3.2 Effects of boundary layer structure on the haze event

3.2.1 Characteristics of horizontal wind fields

Vector wind field reflects the regional flow spatial characteristics; a larger vector wind indicates better dispersion conditions for air pollutants, and vice versa (Wu et al., 2007). Figure 4 shows the average daily 10-m wind fields over Liaoning during December 16–21, 2016. Liaoning was dominated by the southwesterly and westerly flows on December 16, and since the following day the central Liaoning City Cluster was mainly controlled by the southeasterly flow that was favorable for the transportation of water vapor from the Bohai Sea to this region and resulted in high ambient *RH* condition. The daily mean wind speed over the central part of Liaoning decreased day after day from December 16 to 20, which was favorable for the accumulation of air pollutants in this region. With the arrival of cold and dry air masses brought by the strong northeasterly flows on December 21, the heavy haze event ultimately ended.

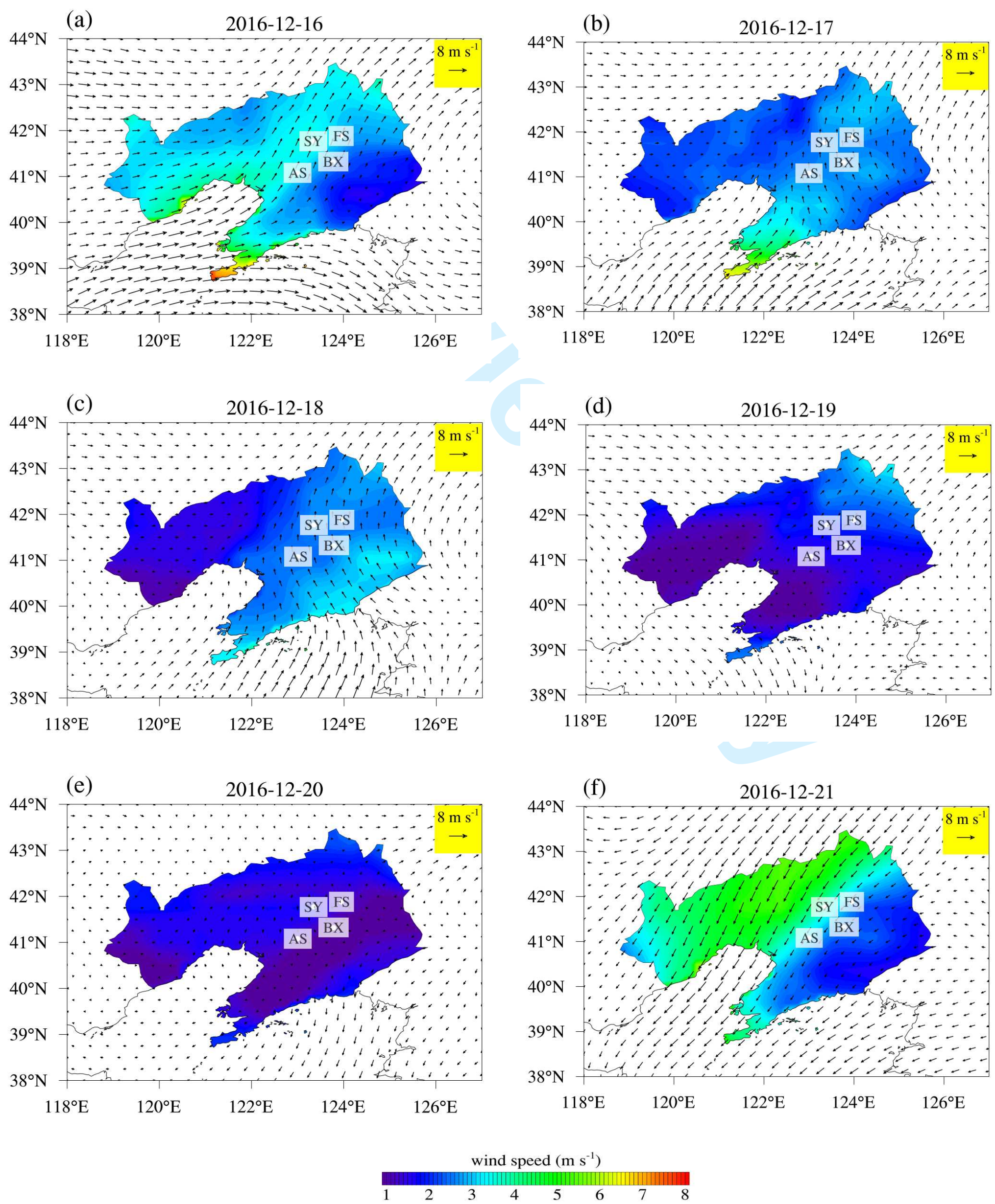


Fig. 4. Spatial variations of the daily mean wind field retrieved from the ECMWF reanalysis data over Liaoning province from December 16 to 21, 2016. SY, FS, AS, and BX represent Shenyang, Fushun, Anshan, and Benxi, respectively.

3.2.2 Characteristics of vertical wind distribution in Shenyang

The vertical distribution of vector wind from 02:00 LT on December 18 to 02:00 LT on December 22, 2016, measured from the boundary layer experiment in Shenyang, is shown in Fig. 5. It can be seen that during 02:00–11:00 LT on December 18 wind speed at all heights below 2 km decreased rapidly with time, and wind direction rotated with increasing height in a clockwise direction. Meanwhile, PM concentrations at surface began to increase sharply (Fig. 2a). Weak southerly and southwesterly flows then prevailed until 11:00 LT on 19 December, corresponding with $PM_{2.5}$ increasing to approximately 300 μg m^{-3} (Fig. 2a). After, wind speed was still very small at low altitudes (< 600 m), whereas at high altitudes, winds fluctuated frequently, contributing to the fluctuation of PM concentrations.

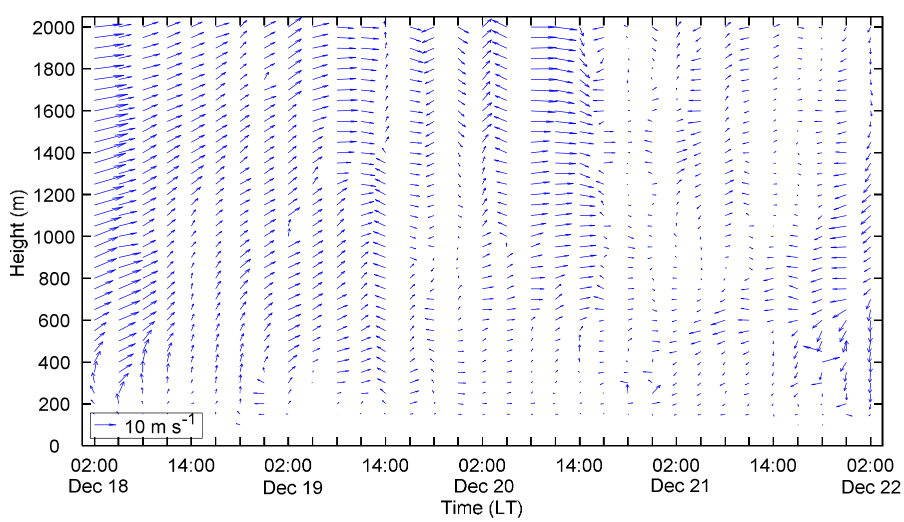


Fig. 5. Vertical distribution of vector wind from the sounding data in Shenyang from

02:00 LT on December 18 to 02:00 LT on December 22, 2016.

3.2.3 Characteristics of vertical temperature distributions in Shenyang

The vertical distribution of air temperature based on sounding data from 02:00 LT on December 18 to 02:00 LT on December 22, 2016 in Shenyang is shown in Fig. 6. With the increasing PM concentrations during the haze event, T_a in the boundary layer decreased obviously, and the depth of the warm advection declined until 14:00 LT on December 20. These stable and upper-layer warm atmospheric conditions were very favorable for the maintenance of the haze pollution event.

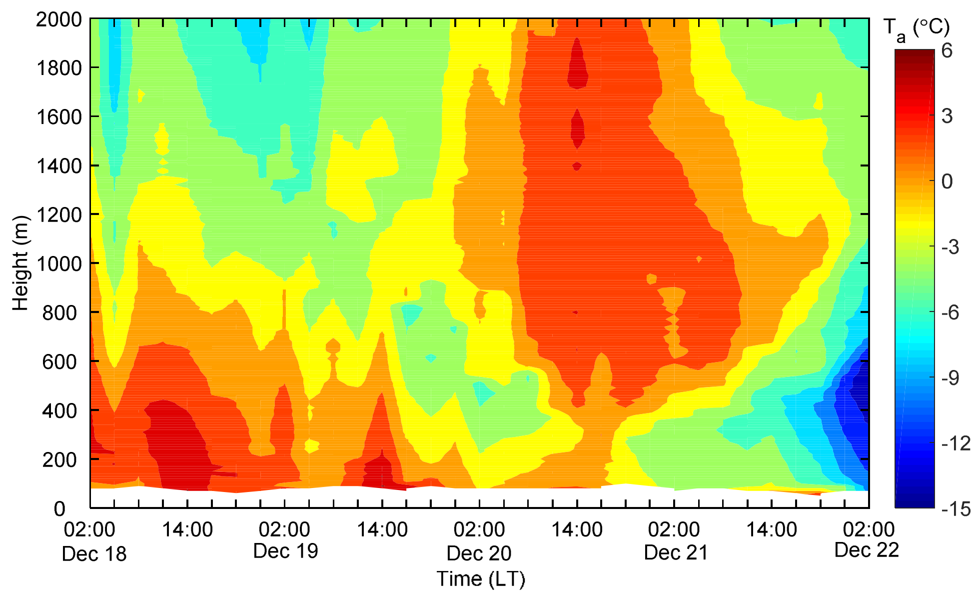


Fig. 6. Vertical distribution of air temperature from the sounding data in Shenyang 02:00 LT on December 18 to 02:00 LT on December 22, 2016.

To clearly outline the atmospheric stability in ABL, Fig. 7 shows potential temperature profiles in Shenyang at 05:00, 11:00, 17:00 and 23:00 LT from December 18 to 22, 2016. From 05:00 LT on December 18 to 05:00 LT on December

19, a potential temperature inversion layer existed from the surface to the height of 1500 m, and the inversion intensity gradually increased with time. During this period, the surface $PM_{2.5}$ concentration increased from 123 to 209 μg m^{-3}. After, θ varied very small at the low altitudes of ABL (< 800 m), but the enhancement of the potential temperature inversion was apparent at high altitudes of ABL. The potential temperature inversion intensity gradually increased from 8.9 K km^{-1} at 17:00 LT on December 19 to 15.8 K km^{-1} at 23:00 on December 20. Additionally, the bottom of inversion height gradually decreased from approximately 900 m at 17:00 LT on December 19 to approximately 300 m on 23:00 LT on December 20, corresponding to a very high PM concentrations on the following day. After that, the bottom of inversion height increased to 900 m again at 11:00 LT on December 22, which strengthened the vertical mixing of air pollutants and favored with the dilution of air pollutants at surface. It should note that the warm advection near the ground at 17:00 and 23:00 LT on December 19, 21, and 22 was mainly due to the heat island effect over the urban region.

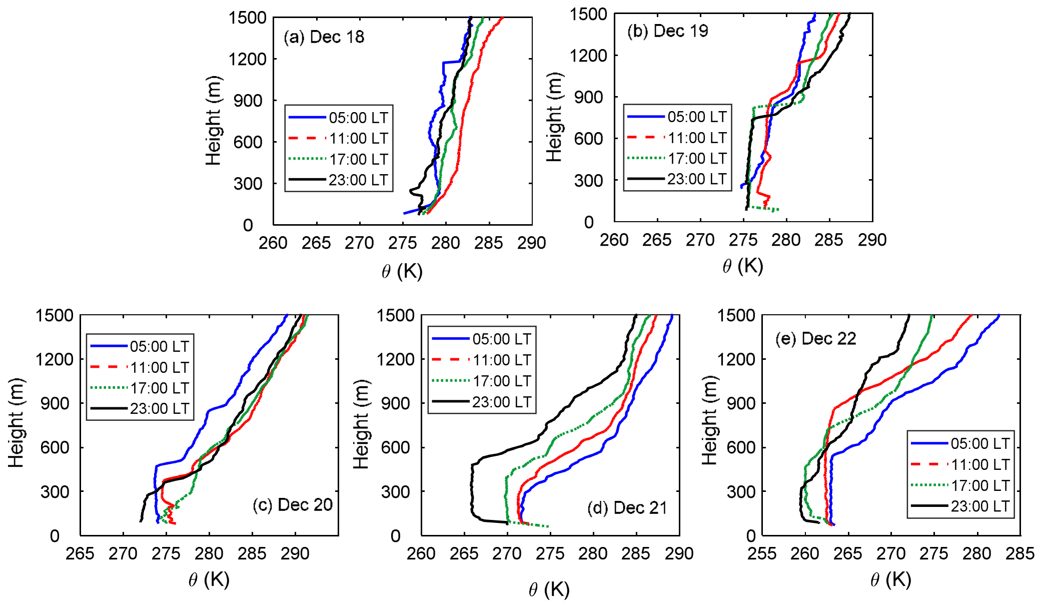


Fig. 7. Potential temperature profiles from the sounding data in Shenyang at 02:00, 08:00, 14:00 and 20:00 LT from December 18 to 22, 2016.

3.2.4 Evolution of ABLH in Shenyang

The ABLH plays an important role in the evolution of haze episodes. Decreasing the height of ABL can normally hold the pollutants within the shallow surface layer, suppress the vertical atmospheric dilution and finally lead to regional environment shrouded by pollution (Kim et al., 2007; Leng et al., 2016). The ABLH estimated using sounding data was plotted in Fig. 8. The regular diurnal variation of ABLH, i.e., highest in the middle of the day and lowest at nighttime, was not so typical during heavy pollution period. From 02:00 LT on December 18 to 11:00 LT on December 19, ABLH was mostly below 400 m, and $PM_{2.5}$ and PM_{10} concentrations during this period reached 265 and 370 μg m^{-3}. When the ABLH increased rapidly to 900 m at 14:00 LT on December 19 and remained larger than about 600 m until 08:00 LT on December 20, $PM_{2.5}$ and PM_{10} concentrations dropped to 142 and 180 μg m^{-3}, respectively. As ABLH remained lower than 400 m from midday on December 20 to midday December 21, the air pollution in the near-surface layer enhanced again. On the whole, the ABLH measured by ball sounding was typically below 400 m during heavy pollution episodes. Such shallow ABL led to high PM concentration in the near-surface layer.

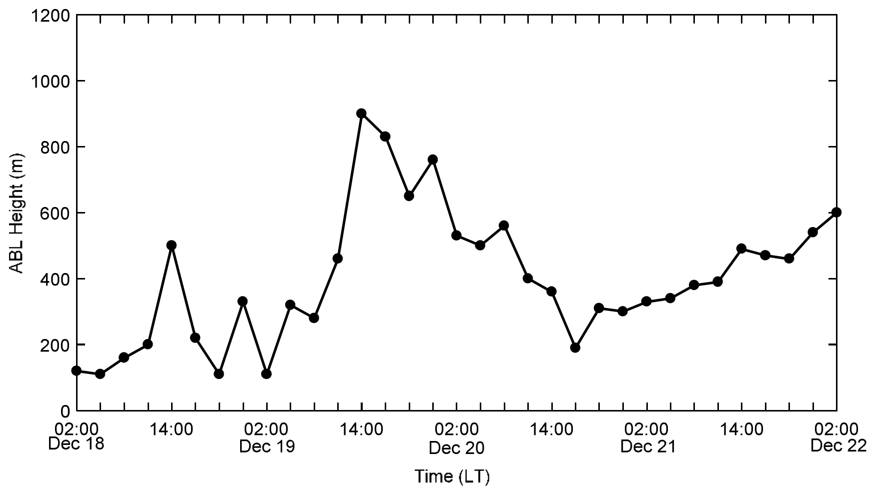
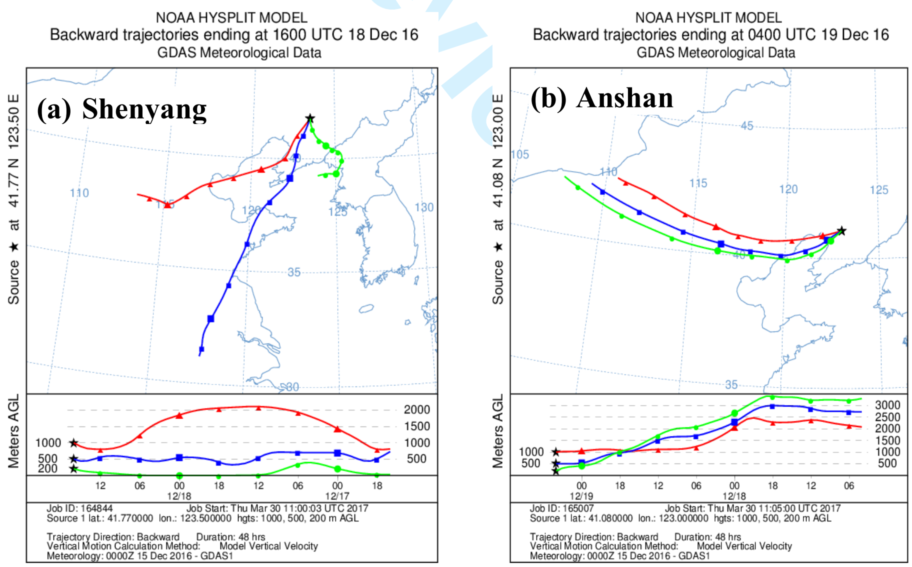


Fig. 8. Evolution of atmospheric boundary layer height (ABLH) from the sounding data in Shenyang.

3.3 Impacts of air mass pathways

Different aerosol transportation paths were observed in the four cities during the haze event according to the 2-day back trajectory analyses at 200, 500, and 1000 m AGL (Fig. 9). The ending time of these back trajectory simulation is listed in Table 1, corresponding with the first peak when $PM_{2.5}$ > 200 μg m^{-3}. The air masses at 200 m AGL were generated from the Bohai Sea and passed through North Korea and southeastern Liaoning before arriving at Shenyang, Fushun, and Benxi. These air masses carried water vapor and led to high *RH* conditions. However, the air masses at all three altitudes in Anshan originated from western China (Fig. 9b), resulting in lower *RH* in Anshan than in the other three cities (Fig. 2j). The transportation paths of air masses at 1000 m AGL in Fushun and Benxi were similar to that of the air mass that arrived in Anshan. The air masses at the middle altitude of 500 m AGL in Shenyang originated from the North China Plain, where anthropogenic activities are intense and severe haze pollution is common. The transport pathways may demonstrate that in addition to the high local emissions of aerosols, the trans-boundary transport of aerosols from the North China Plain could play a role in exacerbating the air pollution.



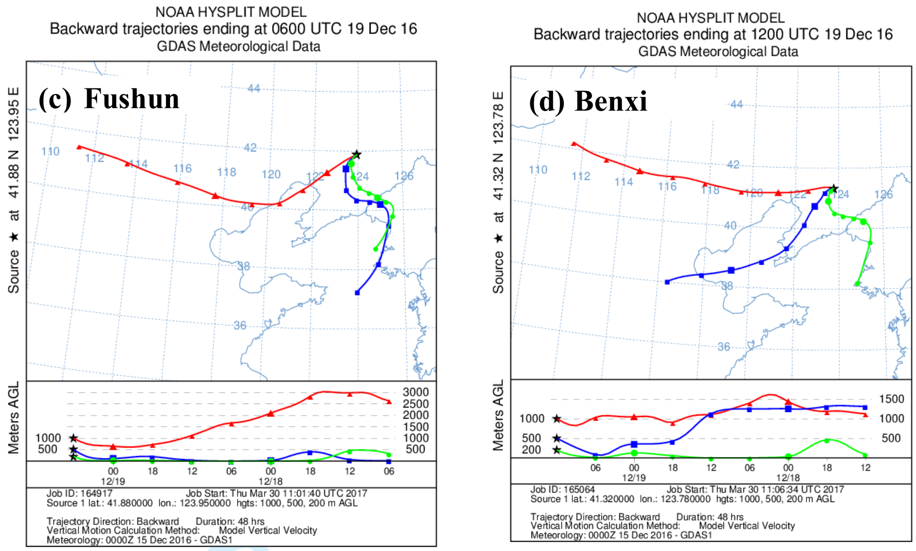


Fig. 9. The 48-h backward trajectory in (a) Shenyang, (b) Anshan, (c) Fushun, and (d) Benxi starting from the first peak of the PM concentration during the haze event.

4. Conclusion

The characteristics of the ABL structure during a persistent, severe regional haze event over the central Liaoning City Cluster during December 16–21, 2016 were analyzed based largely on measurements from an ABL observational experiment and PM concentrations at the surface. The mean $PM_{2.5}$ concentration during the haze event was larger in Anshan (158.3 ± 22.2 μg m^{-3}) and Shenyang (157.9 ± 31.0 μg m^{-3}) and smaller in Fushun (121.3 ± 48.9 μg m^{-3}) and Benxi (135.6 ± 60.8 μg m^{-3}). The distribution of daily horizontal wind fields at 10 m that were retrieved from the ECMWF reanalysis data during December 16–21 were strongly related to allocation of the surface pressure field. A southerly flow in the near-surface layer prevailed over the most regions of Liaoning and brought water vapor from the Bohai Sea, resulting in a high ambient relative humidity (*RH*) condition (60–98%). Wind speed (*U*) decreased rapidly after December 16, and the superposition of a weak wind field with weak horizontal wind resulted in air stagnation, ultimately causing deterioration in air quality during the haze event. A potential temperature inversion layer existed within the entire ABL at the earlier hazy episode, such stable atmospheric conditions were very favorable for the formation and maintenance of the haze pollution event. After, the inversion layer enhanced apparently, with the bottom varying between 300 and 900 m, corresponding to the fluctuation of PM concentration at surface. The ABLH measured by ball sounding was typically less than 400 m during a heavy pollution episode and exhibited a negative correlation with $PM_{2.5}$. Such a low ABLH would concentrate pollutants in the near-surface layer.

The back trajectory analyses indicated that the air masses at the lower altitude of 200 m AGL in all cities originated from North Korea and passed over the Bohai Sea, except for the air masses arriving in Anshan, which caused lower humidity there compared with that in the other cities. The air masses at the higher altitudes of 500 and 1000 m AGL in Shenyang were generated from the North China Plain, where anthropogenic activities are intense and haze pollution is severe. In conclusion, the unfavorable meteorological conditions within ABL played as the external reason of this haze formation, besides the anthropogenic emissions of pollutants as the basic cause.

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